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Nonlinear Seismic Analysis of Masonry Infill RC Buildings with Eccentric Bracings at Soft Storey Level

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Abstract

Eccentric bracings are used in steel structures for long time where it serves as lateral load resisting system and improve strength and stiffness of frame along with effective energy dissipation. In the present study, eccentric bracings are used as a means to reduce soft storey effect in masonry infill reinforced concrete (RC) building. Masonry infill buildings with open first storey are usual choice for almost every general multi-storey construction in India, despite the building's palpable vulnerability to strong ground motion earthquakes. Among other strengthening methods, eccentric bracings could be an advantageous scheme as it provides lateral stiffness and ductility to structure with greater economy and also provides free space for commuting of vehicle at soft storey level. It has been seen that introduction of soft storey in building leads to concentration of damage in that storey while the building suffers only slight damage. Hence, eccentric bracings in soft storey need to be designed in such a way that they act as fuse during major earthquake events. The seismic performance of eccentric bracings for a seven storey building located in Indian seismic zone – V as per Indian standard code 1893-2002 are investigated using nonlinear static pushover analysis. A parametric study involving parameters such as shape of eccentric bracing, area of section, amount of eccentricity etc. are performed for selecting the type of eccentric bracing. The results of pushover analysis, reported in terms of storey drift demand and collapse fragility curve, showed that buildings with eccentric bracings have lower drift demand and probability of collapse.

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1. Introduction

The building construction in India is generally of masonry infill reinforced concrete (RC) construction. In case of multi-storey buildings, a common attribute is to keep its first storey free from masonry infill. This is done mainly to fulfil parking requirements of occupants. This characteristic, owing to abrupt decrease in stiffness, introduces a tangible vulnerability under seismic occurrence. Although this soft storey could be in any storey but according to usual practices it is provided at first storey.

The vulnerability of this type of construction was first recognized in Olive View hospital building during San Fernando earthquake, 1971. The vulnerability of soft storey building in India was observed during Bhuj earthquake, 2001, a 6.9 Richter magnitude earthquake, in which many building with this type of vertical irregularity collapsed entirely owing to failure of soft storey columns and beams [1, 2]. After this earthquake, numerous investigations have been made in soft storey buildings and masonry infill buildings in India. The lateral stiffness of first storey in soft storey building is very less compared to other storeys which are infill with masonry, which results in concentration of large seismic forces, plastic hinges and consequently higher drift demand at that storey. Researchers and various building codes recommend avoiding type of vertical irregularity in buildings, but can be constructed based on detailed seismic analysis of these building. Since, soft storey buildings undergo large inelastic deformations, nonlinear response history analysis as well nonlinear static analysis is required to assess their performance. Usually, nonlinear static analysis is recommended for low rise buildings which are regular in plan. Indian seismic code IS 1893-2002 [3] also suggests the use of nonlinear static analysis for soft storey buildings. For existing as well as new building with soft storey, there is a need of appropriate strengthening scheme which reduce their vulnerability. The strengthening scheme should also be economically feasible.

Figure 1 Failure of buildings with first soft storey during Bhuj Earthquake, 2001, [1, 2].

In this study, eccentric bracings are used as strengthening scheme for soft storey buildings. The main objectives of the present study are: (i) to perform a nonlinear static analysis using SeismoStruct software [4] on building frames incorporating eccentric bracings of different shapes and moment of inertia, (ii) to study the storey drift demand and fragility curves of these buildings.

Nomenclature

B	beam
C	column
d_s	damage state or performance state of building
Ø	bar diameter
S_d	spectral displacement
$S_{d,ds}$	median value of spectral displacement
SQ	Square
β_{ds}	standard deviation of the natural logarithm of spectral displacement
Φ	standard normal cumulative distribution function

2. Eccentric Bracings in Soft Storey buildings

Among various strengthening options, additions of steel bracing to masonry infill reinforced concrete buildings having soft storey is an effective method of strengthening of soft storey and which is also economically feasible. The added bracing systems give required stiffness to soft storey. Among various types of bracing, X-diagonal bracing has been investigated for strengthening weak or soft storey building by various researchers [5, 6]. It is apparent that X-diagonal bracing hinders the movement of vehicle etc. if provided at first storey level. Also, in developing countries like India, due to constraint of space, parking space at first storey is the only alternative left especially in multi-storey buildings involving different dwellers. In this context, eccentric bracing is logical alternative of X bracing, which would allow free movement of vehicles in first storey along with lateral stiffness. The bracings system would be an effective as well as economical method of strengthening of soft storey [7].

Eccentric bracing is used in steel structures since 1930, though only occasionally and that too for architectural purpose until 1970. After that, eccentric bracings have been investigated and used as structural element in steel structures [8]. This bracing system is preferred over other bracings in steel structures due to its high lateral stiffness with adequate ductility and damage concentration [9].

3. Building Frames and Modelling

3.1. Details of building frame

A 7 storey, 3 bay two-dimensional (2-D) RC building frame is considered for the present study as shown in Figure 2. The height of each storey and width of each bay is 3 m. This frame is representative of general multi-storey construction in India and has been used by other researchers for seismic analysis [10, 11]. The frame is designed according to Indian standard code, IS 456-2000 [12]. The design compressive strength of concrete is taken as 35 MPa and yield strength of reinforcement steel is 415 MPa. The loading and weight on all frames is kept same and weight of masonry acts as uniformly distributed load. The structural details of building frame are shown in Tab. 1; more details can be found in [10].

Table 1 Reinforcement details for frame members [10].

Member	Dimension	Longitudinal reinforcement	Transverse Reinforcement
B1 to B21	230 × 400 mm	3# 16 mm Ø top 2# 12 mm Ø bottom	8 mm @ 150 mm c/c
C1 to C4, C22 to C24	300 × 450 mm	10# 16 mm Ø	8 mm @ 180 mm c/c
C5 to C7, C25 to C28	300 × 450 mm	10# 12 mm Ø	8 mm @ 180 mm c/c
C8 to C10, C15 to C17	300 × 450 mm	12# 16 mm Ø	8 mm @ 180 mm c/c
C11 to C14, C18 to C21	300 × 450 mm	12# 12 mm Ø	8 mm @ 180 mm c/c

The three types of frame are modelled, in order to study the effect of stiffness of masonry infill and soft storey are given below These frames will also be referred to as original frames in which no strengthening scheme is introduced.

1. Bare frame - RC frame without infill
2. Infill frame - RC frame having masonry infill on all storeys
3. Soft storey frame - RC frame having masonry infill on all storeys except first storey.

3.1. Nonlinear modelling

The stress-strain relationship of concrete in compression model is taken from [13, 14]. Maximum compressive strain is taken as 0.002 as specified in IS 456-2000 [12]. The SeismoStruct software automatically calculates confinement factor on the basis of cover thickness which comes out to be 1.2. The frame members are modelled as inelastic force based plastic hinge elements. Nonlinear modelling of masonry infill using equivalent strut model with shear spring [15,16] is employed in the present study. The masonry is connected to beam column junction by pin connection. The eccentric bracings are modelled as beam column elements connected to frame with moment joints.

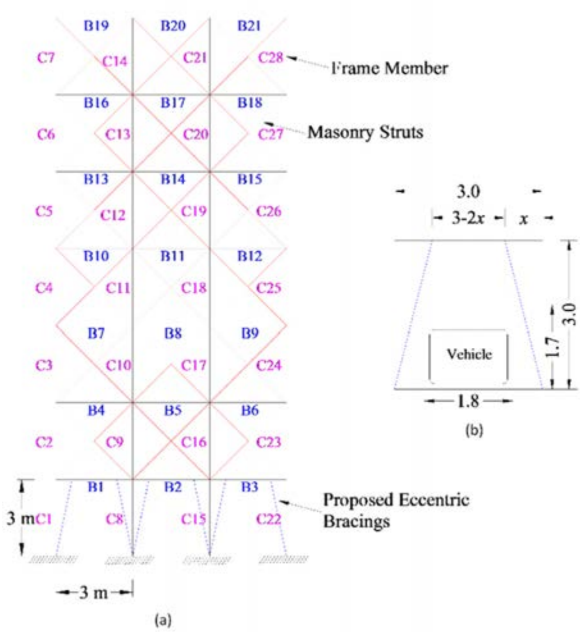


Figure 2 (a) Dimensions of frame member; (b) detail of proposed eccentric bracing.

4. Methodology for nonlinear static analysis

4.1. Using equivalent linearization procedure

Nonlinear static analysis is done by equivalent linearization procedures of FEMA 440. First the pushover curve is converted in acceleration-displacement response spectrum (ADRS) format, plotted between spectral displacement and spectral acceleration. This curve, termed capacity curve, can then be plotted with response spectrum on same graph. The capacity curve is idealised in bilinear form to obtain yield displacement. The bilinear idealisation is done by first assuming a trial performance point. This can be done by equal displacement rule in which an initial slope line is drawn. The response spectrum curve, which is for elastic systems is then modified to give demand spectrum. The modification can be done in various ways as given in FEMA 440. However, in this study Procedure B [17] is employed in which response spectrum curve is modified in relation to ductility and effective damping of structure. The modified response spectrum is termed as demand spectrum or ADRS. The ADRS is further modified with spectral acceleration modification factors to give modified acceleration-displacement response spectrum (MADRS). The performance point is obtained at intersection of capacity curve with MADRS. The whole procedure is illustrated in Figure 3 where capacity curve and demand curves in ADRS format, along with performance point are shown.

4.2. Using Fragility Curves

The performance of building can also be assessed by using fragility curves. Fragility curves correspond to fragility function, a mathematical function which expresses the probability of occurrence of event with respect to ground excitation (in form of acceleration, velocity or deformation). A fragility function may also be defined as the lognormal cumulative distribution function of the capacity of an asset to resist an undesirable limit state [18]. Fragility curves visually show the probability or chance of collapse of structure for given earthquake ground motion. The analysis involved in fragility needs to be nonlinear to capture large deformation characteristic occurring due to seismic loads. Nonlinear response history analysis or incremental dynamic analysis is recommended. However, for buildings of medium height nonlinear static analysis (pushover analysis) can also be used to obtain the fragility curves of building. This is usually done through FEMA earthquake loss estimation methodology- Hazus. The updated version of Hazus methodology is Advanced Engineering Building Module (AEBM) which is useful in developing building specific damage and loss functions [19]. Hazus AEBM methodology is used in this study to assess seismic performance of various building models including soft storey buildings.

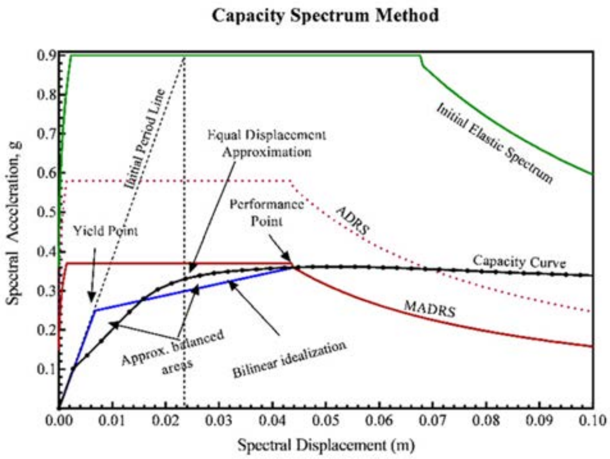


Figure 3 Capacity curve and demand curves in ADRS format, along with performance point.

The probability of exceeding or being in a particular damage state d, $P[ds|S_d]$, for a given spectral displacement, S_d, (or other seismic parameter) is given by lognormal standard cumulative probability distribution equation (1). This expression when plotted against S_d gives the required fragility curve for corresponding damage state.

$$P\left[ds \mid S_d\right] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \tag{1}$$

5. Parametric Study

The parametric study is performed in two parts. Firstly, two different shapes of cross-section, circular and square are used in soft storey frame and by varying their moment of inertia. The sections are taken from Tata Structural hollow section specifications. The dimensions of circular and square cross-section considered for parametric study are shown in Table 2 and 3, respectively. Based on the analysis results, a section with appropriate moment of inertia is selected and then eccentricity of bracing, *x* (as shown in Figure 2) is varied as 0.50 m, 0.55 m, 0.60 m, 0.65 m, 0.70 m, 0.75 m, 0.80 m for that section.

Table 2 Dimensions of bracing elements with circular cross section.

Designation	Nominal Bore, (mm)	Outside Diameter (mm)	Thickness (mm)	Area of cross section, (cm^2)	Unit weight, (kg/m)	Moment of Inertia, cm^4
Circle 25	50	60.3	3.6	6.41	5.03	25.88
Circle 50	65	76.1	3.6	8.2	6.42	54.02
Circle 100	80	88.9	4	10.7	8.36	96.36
Circle 200	100	114.3	3.6	12.5	9.75	192.03
Circle 270	100	114.3	5.4	18.5	14.5	274.5

6. Results and Discussions

The analysis results obtained from nonlinear static analysis are used to evaluate storey displacement, storey drift demands and fragility curves. Due to large variations in interstorey drifts of various storeys, drifts are plotted on logarithmic scale. The responses are corresponding to the performance point of building under the response spectrum earthquake corresponding to Indian Seismic Zone –V. Figure 4 (a) shows interstorey drift of general frames from which it is clear that soft storey frames have large drift demand during an earthquake.

Table 3 Dimensions of bracing elements with square cross section.

Designation	Length of Side (mm)	Thickness (mm)	Area of cross section, (cm^2)	Unit weight, (kg/m)	Moment of Inertia, cm^4
SQ25	50	4.5	7.67	6.02	25.5
SQ50	60	4.8	10.01	7.85	49.22
SQ100	80	3.2	9.57	7.51	92.7
SQ200	92.5	4.5	5.14	11.88	187.57
SQ270	100	5	18.36	14.41	271.1

6.1. Effect of moment of inertia and section shape of bracing

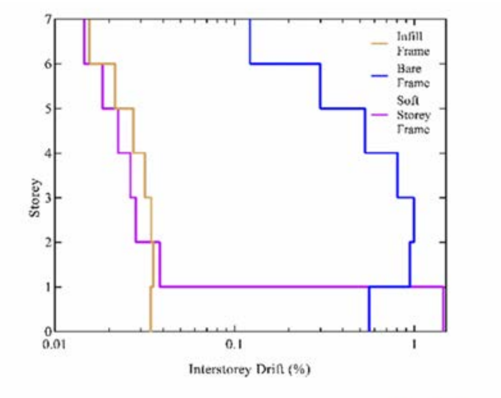
Interstorey drift of original frames along with strengthened frames of different shape and moment of inertia is shown in Figure 4 and storey displacements are shown in Figure 5. Building frames strengthened with eccentric bracings show phenomenal decrease in first storey displacement as well as storey drift although effect of varying moment of inertia of bracing is not proportionate. It is also observed from Figure 6 that circular section performed better than square section during an earthquake.

6.2. Effect of eccentricity

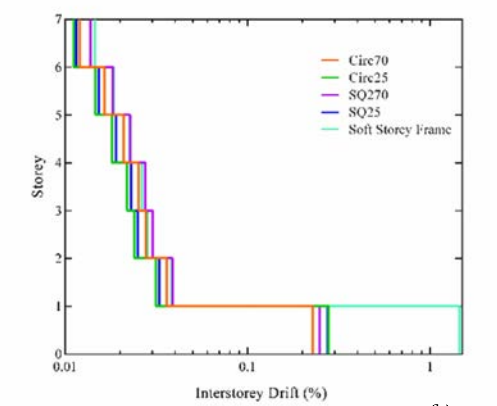
The effect of eccentricity on storey displacement and storey drift of soft storey building is given in Figure 7. It is observed that as distance *x* increases, the storey drift decreases, hence as far as possible the bracings should be connected near the middle of the beam.

6.3. Fragility Curves

The fragility curves for bare frame, infill frame and soft storey frame are plotted in Figure 8 (a) which shows that probability of exceedance of given damage state is more for soft storey frame. Fragility curves of eccentrically braced frames along with that of soft storey frame are given in Figure 8 (b) which shows that probability of exceedance of given damage state is decreases for eccentrically braced frames. The fragility curves for frames with different eccentricity are very similar and hence are not shown.



(a)



(b)

Figure 4. Interstorey Drift (log) for different frames (a) General frames (b) Strengthened frames.

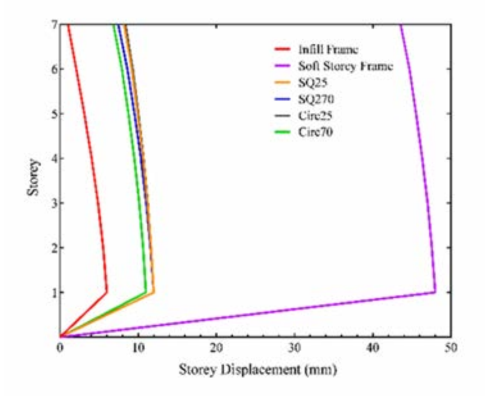


Figure 5. Storey Displacement for frames with different moment of inertia.

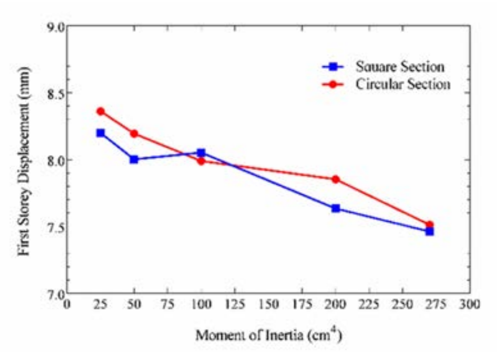
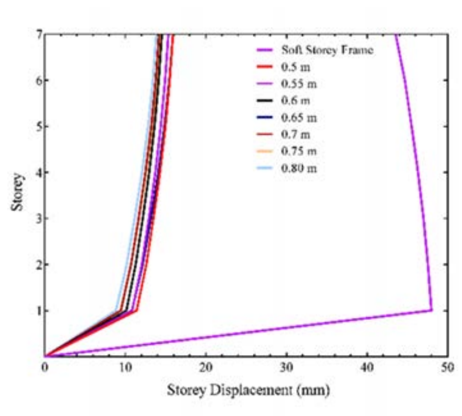
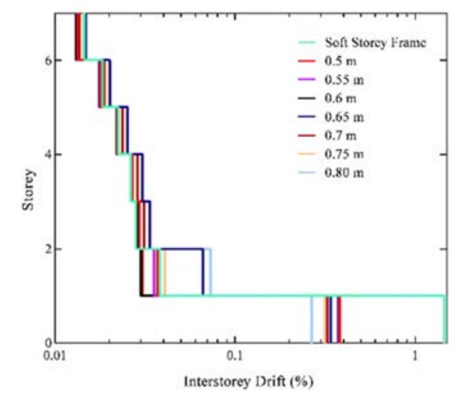


Figure 6. Comparison of first storey displacement for frames with different moment of inertia.

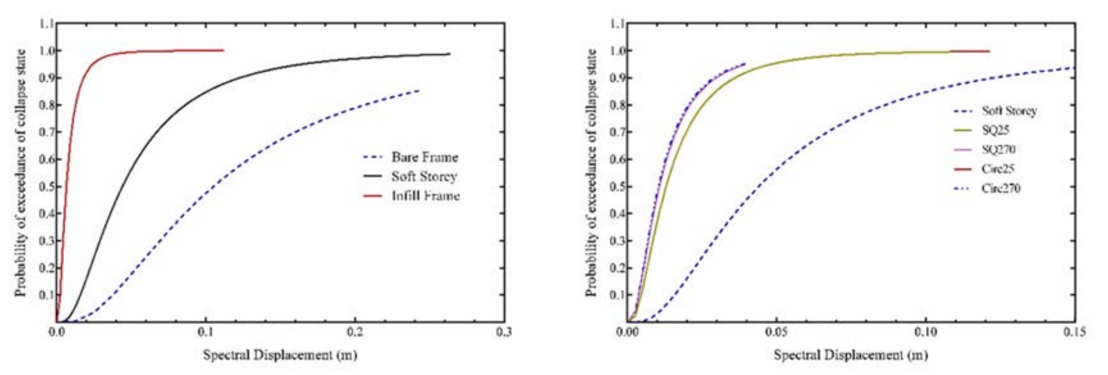


(a)



(b)

Figure 7 (a) Interstorey drift; (b) Storey displacement for frames with different eccentricity distance (*x*).



(a) (b)

Figure 8 Fragility curves for (a) General frames; (b) Strengthened frames.

7. Conclusions

Masonry infill RC soft storey buildings with first storey free of infill is generally a preferred configuration of multi-storey buildings in India. Due to lack of stiffness in first storey, these building undergo large displacements at first storey level and hence are highly vulnerable under seismic loads. Nonlinear static analysis is employed to incorporate inelastic displacements occurring at soft storey level. A frame representative of general multi-storey buildings in India is selected from previous study. The results clearly show that large displacements occur at first storey level in soft storey building compared to other type of buildings i.e. bare frame and infill frame. It is also observed that large portion of displacement concentrates in first storey and hence other storeys are undamaged.

An economical scheme of strengthening is introduced which consists of steel eccentric bracings placed at first storey which results in increased stiffness of that storey. In practice, the bracings will act as fuse during earthquakes enduring most damage while keeping the building undamaged. The results of nonlinear static analysis show that frames with eccentric bracings have lesser storey drift than that of soft storey frame. Parametric study involving moment of inertia and eccentricity distance is conducted on soft storey frames with eccentric bracings. It is observed that increasing moment of inertia does not have proportionate effect on storey drift. Also, the eccentricity distance has some effect on drift and it is recommended to connect the bracings at middle of beams, if possible.

Further, fragility curves are plotted from nonlinear static analysis which visually shows the probability of exceedance of damage state i.e. collapse. Fragility curves for soft storey frames with bracings show that probability of collapse is reduced in comparison to soft storey frames. Hence, it is concluded that steel eccentric bracings could be an effective strengthening scheme for masonry infill reinforced concrete soft storey buildings.

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